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THE LAVA TIDE, SEASONAL TILT, AND THE VOLCANIC CYCLE

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I. *The lava tide.*—Chamberlin has written "pronounced tidal movements might be expected in the necks of volcanoes if they were connected with large reservoirs of lava below, but if there is any response to tidal strains at all, it is scarcely detectable."[1] In July–August, 1919, at the Hawaiian Observatory the authors investigated this question for a month, assisted by Messrs. Sumner Roberts and Charles Thorndike.[2]

The work was stimulated by test measurement made by Mr. Jaggar January 4, to 14, 1913, at Halemaumau lava pit. A telescopic alidade was set up on sill of instrument shelter built at pit's edge and numerous vertical angles were read for 10 days to measure hourly change of level of liquid lava pool against a vertical portion of its shore line. It was found that there were variations in lava level of from 1 to 6 feet per hour sometimes up and sometimes down. For four days forenoon levels were low and night levels were 5 to 10 feet higher. During a run of 22 hourly readings January 7 the lava rose and fell in pulsations suggesting a six-hour periodicity, the risings sudden and the sinkings slow, with culminations around 12 or 6 o'clock both night and day.

On July 21, 1919, transit measurement every 20 minutes for a month was instituted, Messrs. Jaggar, Finch, Emerson, Roberts, and Thorndike each taking turn in shifts, and making readings on a rim station as datum. Two points on the edge of the liquid lava lake and two points on the pit floor or "bench magma" were incessantly measured with reference to the datum station horizontally and vertically, and the index error of the level bubble was always read. Releveling was frequent as the instrument shelter was itself one of the moving points on the floor, the ground rising during the month. All of this was inside the inner pit Halemaumau of Kilauea Crater, and the shelter was placed near the margin of one of three inner lakes of lava. A triangulation was made every day to locate shelter and floor movements.

From the observatory 2 miles away occasional readings were made to check possible small fluctuations in height of the datum station, and daily readings were made with micrometer telescope on the lava crags that rose above rim of Halemaumau. These distant observations furnished a check wherewith to observe sudden changes or accidents to the datum station. No significant movement of that station occurred. The lava in Halemaumau was very high, the floor area standing as a dome mostly above rim of pit, with the three lakes in clover-leaf pattern as cups or wells puncturing the crest of the dome. Notes on the beginning and ending of the field work will be found in Bulletin of Hawaiian Volcano Observatory under the dates July 19 and August 18, 1919, and illustrations showing conditions, transit shelter, etc., are published in the July, August, and September Bulletins of that year. During the 28 days of measurement beginning July 21 the lake rose 58 feet to August 15 and sank 29 feet thereafter: August 2 to August 12 rather stationary conditions prevailed. The floor rose 50 feet to August 16 and subsided thereafter 6 feet.

It should be explained that floor and pools are both parts of the live red-hot lava column, the floor being covered with a heavy crust that is a heat insulator. This floor lava is a stiff but mobile magna rising by mass tumescence. The liquid lava in cups of the floor rises through wells in the floor substance by gas foaming and maintains shallow pools, apportionate in size to the heating or melting capacity of the gassy flux. The rim of pit is old rock somewhat crevassed and sometimes forced into tumescence by the paste occupying the crevasses below, but in general relatively rigid. It acts as a definite cold boundary or "perilith" for the mobile lava column.

Results of the measurement referred to fixed datum have been plotted for the entire period, and by taking the mean of overlapping five-point summations hourly levels for the liquid lava and the floor lava have been computed. The curve of 20-minute intervals shows a ragged rise and fall of both liquid lava and floor lava, the liquid ranging from zero to 2 feet or more in 20 minutes, the floor from zero to a half foot more or less. The curve develops a crude semidiurnal fluctuation for the liquid ranging from 2 to 7 feet with sharp bends, and a sinusoidal diurnal curve is indicated with a range of from 3 to 5 feet. For the floor lava the curve is made up of flat arching movements running for from 4 to 6 hours each, and compounded into pronounced diurnal sinusoidals with a range of about a foot. These diurnals show best August 2 to 12 when the longer term rising movement tends to flatten out to something approaching stationary lava.

These facts may best be seen by reference to the figures. Figure 1 shows actual results of measurements of the liquid lava fluctuation at 20-minute intervals from 7 p. m. July 24 to 7 p. m. July 28. There is here indicated a definite diurnal rise and fall with the rising movement enduring longer than the falling movement as the net change for the four days was a marked rising of the lava column. It will be seen in this figure also that a semidiurnal movement is strongly suggested.

Figure 2 exhibits the lava movement August 6 to 11. Curves A and B show the liquid lava, C and D the floor lava. Curve A is the diagram of hourly measurements arrived at by overlapping summations. Here pulsations of gas action are evident and from noon to noon there is at first sight little trace of diurnal periodicity. The diurnal characteristics of this portion of the liquid curve show better when we examined by overlapping means the record for eight days. This has been done in curve B. This curve was arrived at by taking, for example, the average movement from noon to 1 p. m. for the five days immediately adjacent to each date; thus for August 6 the average of August 4 to 8, inclusive; for August 7 the average of August 5 to 9, inclusive, etc. The same treatment was accorded the average movement from 1 p. m. to 2 p. m., from 2 p. m. to 3 p. m., etc., so that the curve for the four days really represents an averaged curve for eight days. It is at once seen that a systematic diurnal rise and fall occurs with low levels about 10 p. m. and high levels in the morning. A striking character of the diurnal curve here is its powerful oscillations from about midnight on, decaying or dying away along with subsidence the following afternoon.

The rise and fall of the floor lava (C and D of fig. 2) is represented at C by the 20-minute measurements, reduced to hourly, and at E by the hourly reduced by the five-day overlapping process. In both of these the diurnal rise and fall is very plain with low levels usually in the forenoon and high levels in the night.

Comparing A–B, the liquid, with C–D, the floor, it is evident that the two sets of waves are not in phase, especially for the first three days with respect to the troughs or low levels indicated in this figure. The B

[1] T. C. Chamberlin, The Origin of the Earth, p. 231, University of Chicago, 1918.
[2] Bulletin Hawaiian Volcano Observatory, July to September, 1919.

curve moreover agrees generally in its times of low and high with the facts indicated in Figure 1 representing a period two weeks earlier. And at that time also there was disagreement in phase between liquid and floor, not here figured.

Summing up the facts available we see that these measurements reveal the extraordinary truth that a systematic tide lifts the lava in Kilauea Crater so that for the dates indicated the liquid is high in the morning and low in the evening, and the inner floor is high in the night and low in the forenoon. The range of movement is greater for the liquid than for the floor matter. And finally, it appears from Figure 2 that a gradual rising movement of floor matter begins a half-day, more or less, before the corresponding upward spurt of gas and liquid, and then the floor sinks rapidly to its lowest position a half-day before the gradually subsiding liquid lava reaches its minimum. The two maxima are much closer together than the two minima.

II. *Seasonal tilt.*—At the 1920 meeting of the pan-Pacific conference the writer presented results of tilt measurement with seismographs to show that at Kilauea Volcano excessive tiltings occur, that resolve themselves into decaying quarterly series of monthly waves, with mean directions away from and towards the Mauna Loa center of the Hawaiian volcanic system. It was found that rapid forced movements away from the centrum exhibited accordance with subsequent lava risings, and a reverse movement accorded with sinkings.[3]

Prof. Leo Cotton commented as follows (Pan-Pac. Proc. 1921, p. 324): "Tilt instruments installed in Australia show very large seasonal tilts. A tilt of 5 to 10 seconds' range occurs from winter minimum to summer maximum. The period of the tilts lags several months behind the heat effects. The instruments are placed about 30 feet underground. The tilt records at Kilauea need a year's work to see how the data compare."

The curve of tilt more than three years, 1919–1922, at Kilauea Obervatory, is shown in Figure 3. This is the east-west component, involving directions away from and toward Mauna Loa center. In addition to the above-mentioned short-term waves, more strikingly monthly than quarterly, a marked annual wave of 15 to 25 seconds' tilt accumulation appears, the east movement culminating in winter (December to March) and the west movement in late summer (August to September). Something of the quarterly decay curves exhibited in 1917–18 (pl. 22, Bull. Seis. Soc., December, 1920, v. ante) are shown again in autumn and winter 1919-20. The annual curve is sinusoidal except in 1919 when the September bend is sharp. At the end of this month Mauna Loa broke into violent eruption.

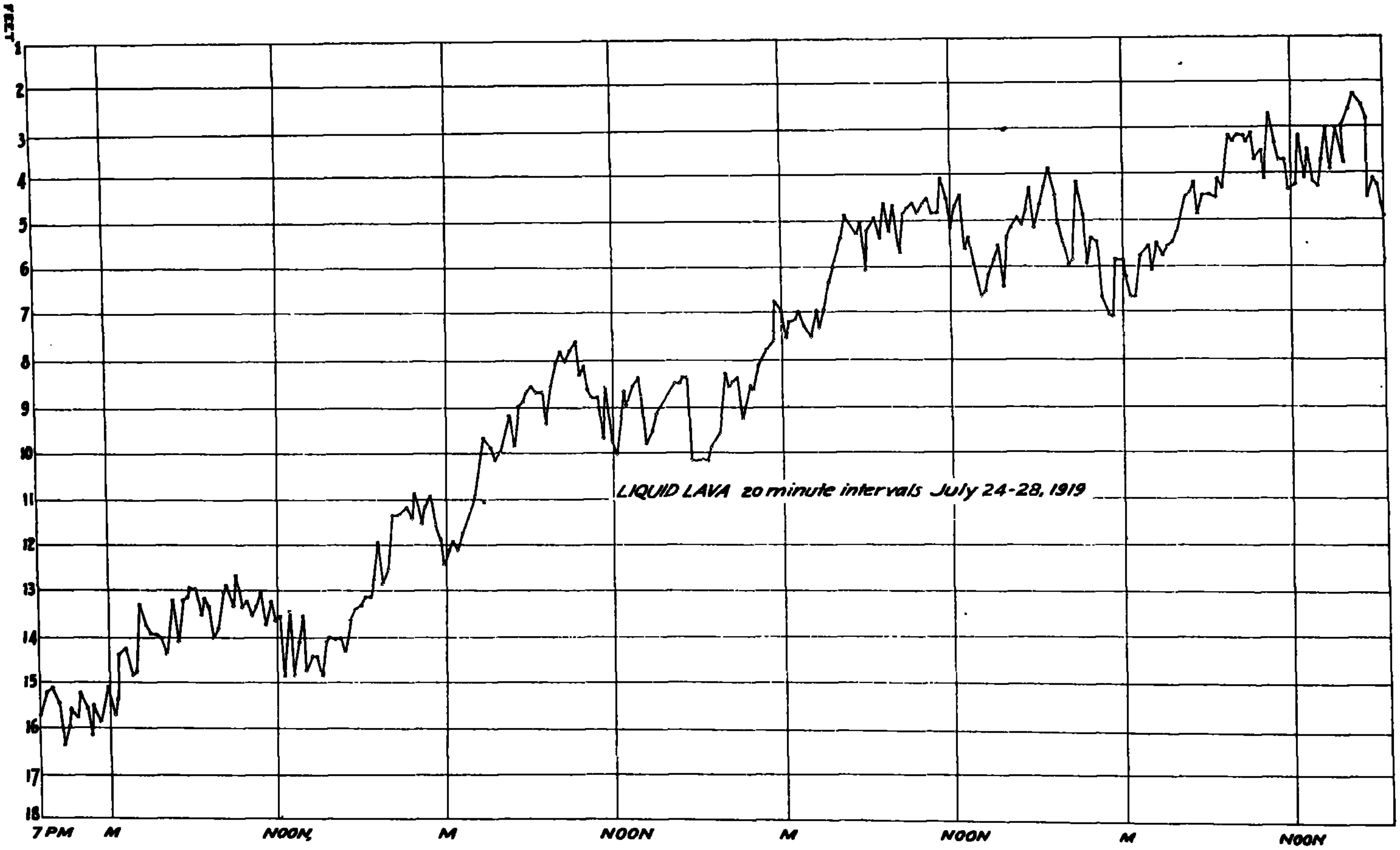

FIG. 1.—Liquid lava fluctuation at Kilauea July 24 to 28, 1919, at 20-minute intervals

This curve supplements previously published data by showing winter tilt waves of wide range and monthly period with accumulation east, and summer decay to short range waves of shorter period with accumulation west. How may this be tied to the volcanic phenomena? In the paper above cited (Seis. Soc.) the writer has exhibited seasonal lava fluctuation centering about equinox. In the first part of the present paper he has shown the presence of daily lava tides.

It is too early in the development of volcano science to present theoretical correlation of these rhythms. This much may be pointed out in comparing volcanic effusion of the Hawaiian system with the tilt in Figure 3. In spring of 1919 Kilauea flooded voluminously with some decline in September. (See fig. 4.) In autumn

[3] Proc. First Pan-Pac. Sci. Conf., Honolulu, 1921, p. 319, and Bull. Seis. Soc. Amer., vol. 10, No. 4, p. 201, December, 1920.

to winter 1919-20 Mauna Loa and Kilauea produced two immense lava floodings. In August, 1920, all of this declined. In winter 1920-21 Kilauea flooded vigorously. In July to August, 1921, this had declined. In winter 1921-22 Kilauea lava rose to a May culmination and outbreak, in craters that had been quiet for 82 years. This was followed by tremendous subsidence *with recovery in September, 1922.* The whole period 1919-1922 shows declining annual tilt and subsiding lava.

ill defined. The Hawaiian system involves four potentially active volcanoes liable to intrusion or extrusion, and an indefinite sea-bottom tract of unknown volcanic proclivities.

The nine-year cycle in Hawaii, however, has been satisfactory for the last three decades, with culminating eruptions on Mauna Loa in 1899, 1907, and 1916-1919. It is now of interest to examine a chart (fig. 4) showing quarterly culminations (highest levels) of Kilauea lava

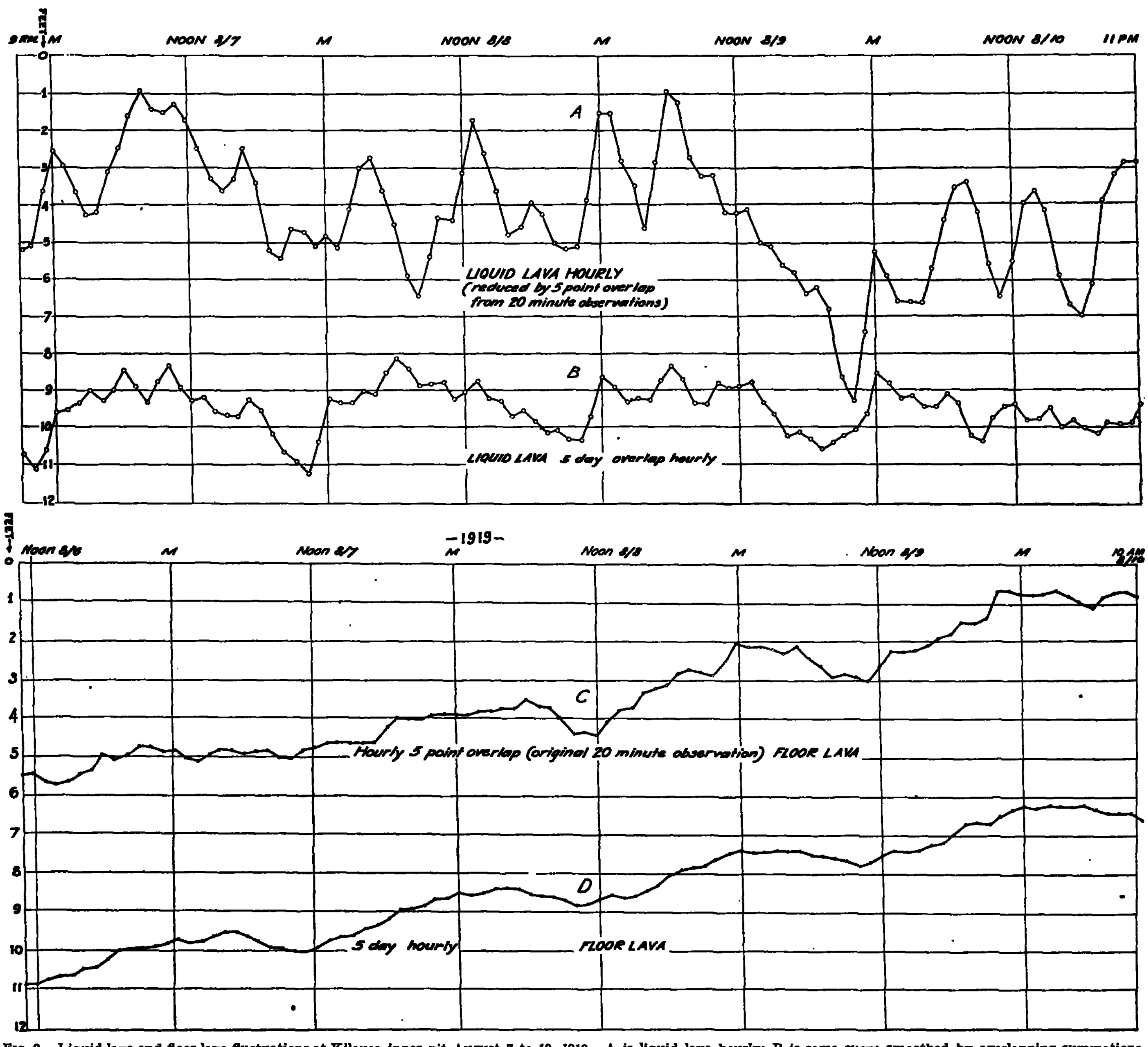

FIG. 2.—Liquid lava and floor lava fluctuations at Kilauea inner pit August 7 to 10, 1919. A is liquid lava hourly; B is same curve smoothed by overlapping summations, inclusive, of eight days; C is floor lava hourly; D is same curve smoothed by overlapping summations.

III. *The volcanic cycle.*—W. L. Green in his "Vestiges of the Molten Globe" (Part II, p. 287) concluded that a nine-year period was the "full" period for the Hawaiian eruptive cycle, but that frequently the periods were shorter. Phillips, Mercalli, and others have experimented with Vesuvian periods, and have encountered difficulties. The trouble is that the volcanic *system* that demands extravasations is likely to be geographically

for 14 years past, with every measurement since the summer of 1911 under the supervision of the Hawaiian Volcano Observatory.

The quarters are centered about the months March, June, September, and December so as to concentrate solstice and equinox. *Highest level* for the three months, including one month on each side of the month named, is what the curve shows. The black vertical lines indicate the low limit reached by one or more pronounced subsidences, which sometimes happened *within* a three-months' period. Sudden risings within a quarter are indicated by broken lines. MF and KF mean, respectively, "Mauna Loa flowing" or "Kilauea flowing," *including both flank outflows and voluminous flows* within the greater craters.

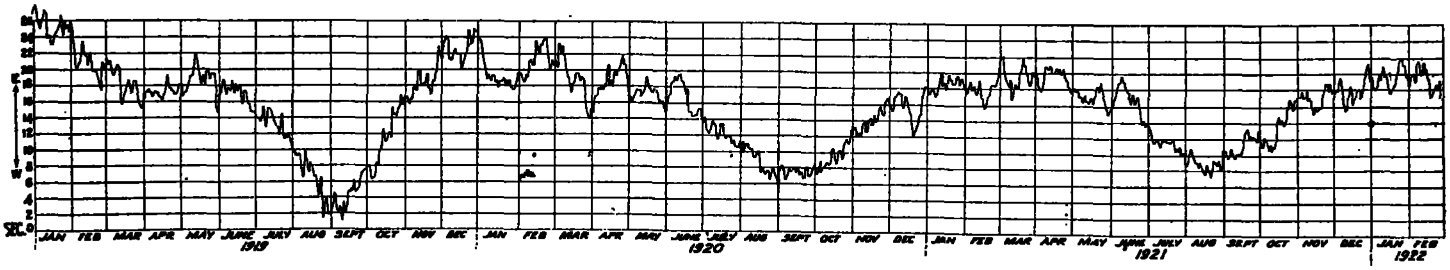

FIG. 3.—Curve of east-west seasonal tilt at Kilauea Observatory from 1919 to 1922, from daily measurements

It will be seen that 1913 was a low-level year of remarkable significance, and that in 1923 another low level appears to be approaching. The wide and gradual low-level peak of the curve for 1913 is very different from the sharp drop and recovery of the year 1922–23. These sharp drops appear to occur in groups of three with progressive increasing depressions for each triplet. The flowing concentrated about the high-level peak of 1918–20 and tapered off on both sides. It seems probable that the present cycle is an exceptional one, representing perhaps a 60-year crisis, and so its length may be considerably more than nine years. The history of cycles since 1868 indicates that there were two of 12 years' duration, with an average of 8.5 years.

One remarkable character of the 1913–23 cycle should be stated and then this paper is finished. That is the sequence to date of outflow vents progressively lower on the mountains. 1914 produced eruption in summit crater of Mauna Loa, elevation 13,000 feet. 1916 and 1919 were on south flank Mauna Loa, 8,000 feet. 1920 was on south flank Kilauea, 3,500 feet. 1922 was on east flank Kilauea, 2,500 feet. The suggestion of a subsiding subterranean lava column, seeking relief in spasms of gas pressure throughout the cycle, is unavoidable.

The purpose of this paper will have been achieved if it demonstrates that the crust of the earth at an active volcanic belt is highly mobile, exhibiting tides and cycles in the lava, and tiltings of the ground that are remarkable and systematic in relation to the seasons and in relation to the volcanoes.

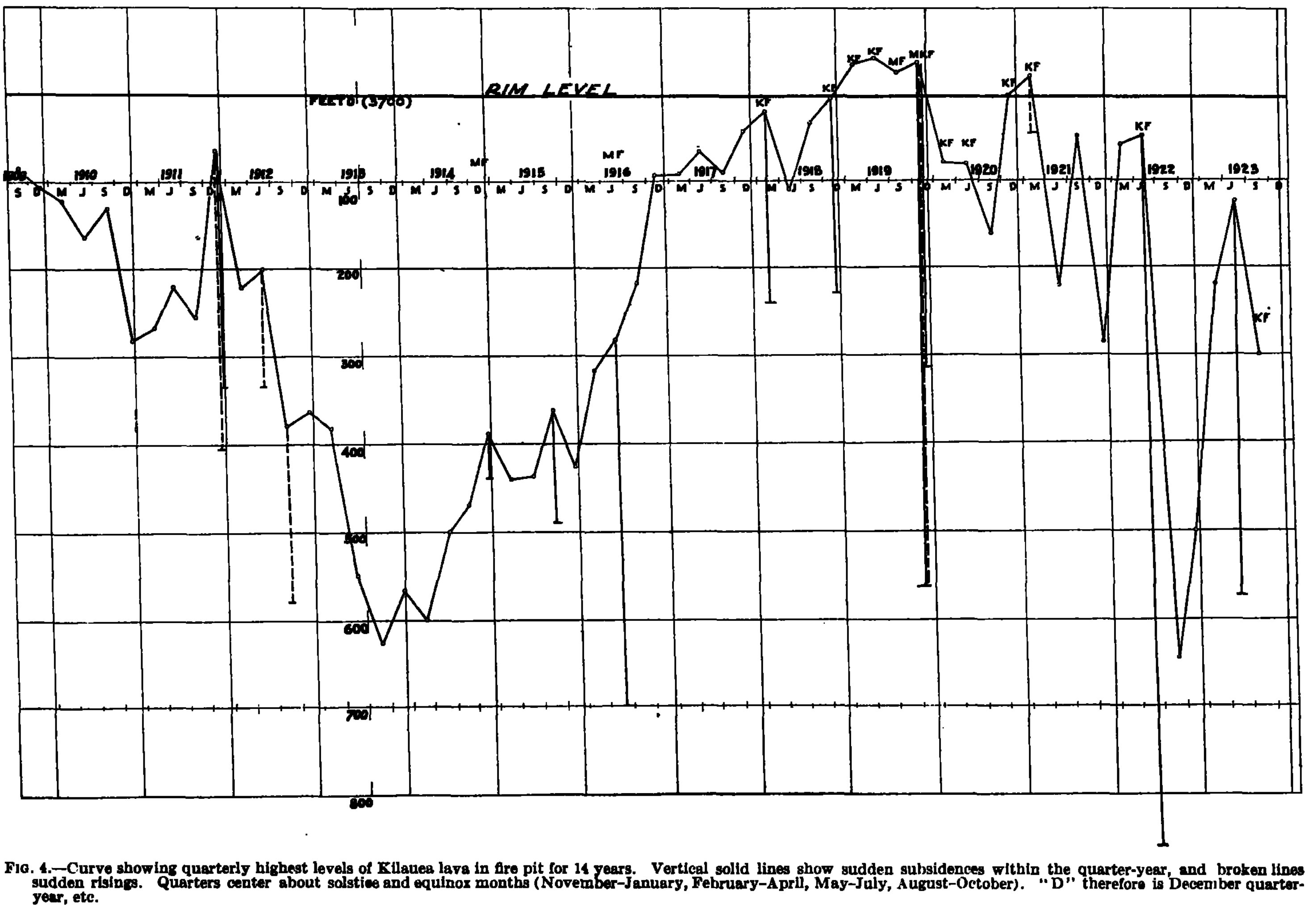

FIG. 4.—Curve showing quarterly highest levels of Kilauea lava in fire pit for 14 years. Vertical solid lines show sudden subsidences within the quarter-year, and broken lines sudden risings. Quarters center about solstice and equinox months (November–January, February–April, May–July, August–October). "D" therefore is December quarter-year, etc.